UNIVERSITY OF ALBERTA

Context Sensitivity

CMPUT 416/500
Foundations of Program Analysis

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Previously

- Inter-Procedural Data-Flow
- Inherited vs Synthesized Analysis Info
- Caller-Callee Relationships
- Valid/Invalid Paths
- Staircase of Calls and Returns
- Demand-Driven Analysis
- Types of Contexts
- Important Language Features

How can we conduct context-sensitive analyses?

Method Cloning

Method Cloning

```
int i = 0;
int j = inc(i);
int k = inc(j);
```

Method Cloning

```
int inc(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;
int j = inc(i);
int k = inc(j);
```

Method Cloning

```
int inc1(x){
  int y = x+1;
  return y;
}

int inc2(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;
int j = inc1(i);
int k = inc2(j);
```

Method Cloning

- ❌ Inefficient: too many copies for real programs
- ❌ Expensive operation
- ❌ Recursion!
- ✅ Yet simple and easy to understand

```
int inc1(x){
  int y = x+1;
  return y;
}

int inc2(x){
  int y = x+1;
  return y;
}

int i = 0;
int j = inc1(i);
int k = inc2(j);
```

Method Inlining

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```
int i = 0;
int j = inc(i);
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Method Inlining

```
int inc(x){
  int y = x+1;
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int i = 0;
int j = inc(i);
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Method Inlining

```
int inc(x){
  int y = x+1;
  return y;
}
```

```
int i = 0;

int x1 = i;
int y1 = x1+1;
int j = y1;

int k = inc(j);
```

Method Inlining

```
int i = 0;

int x1 = i;
int y1 = x1+1;
int j = y1;

int x2 = j;
int y2 = x2+1;
int k = y2;
```

Method Inlining

- ✗ Lost procedure abstraction
- ✗ Exponential blow-up
- ✗ Recursion!
- ✓ One procedure => intra-procedural

```
int i = 0;

int x1 = i;
int y1 = x1+1;
int j = y1;

int x2 = j;
int y2 = x2+1;
int k = y2;
```

… so what do we do?

Context Sensitivity

Context Sensitivity

Call Strings

Functional

Context Sensitivity

Call Strings

Functional

- Extend facts with context strings
- Re-evaluate procedure for each extension
- ✅ Universally applicable
- ❌ Recursion!

Context Sensitivity

Call Strings

- Extend facts with context strings
- Re-evaluate procedure for each extension
- ✅ Universally applicable
- ❌ Recursion!

Functional

- Compute summary function per callee
- Apply summary to each context
- ✅ Recursion!
- ❌ Not always applicable

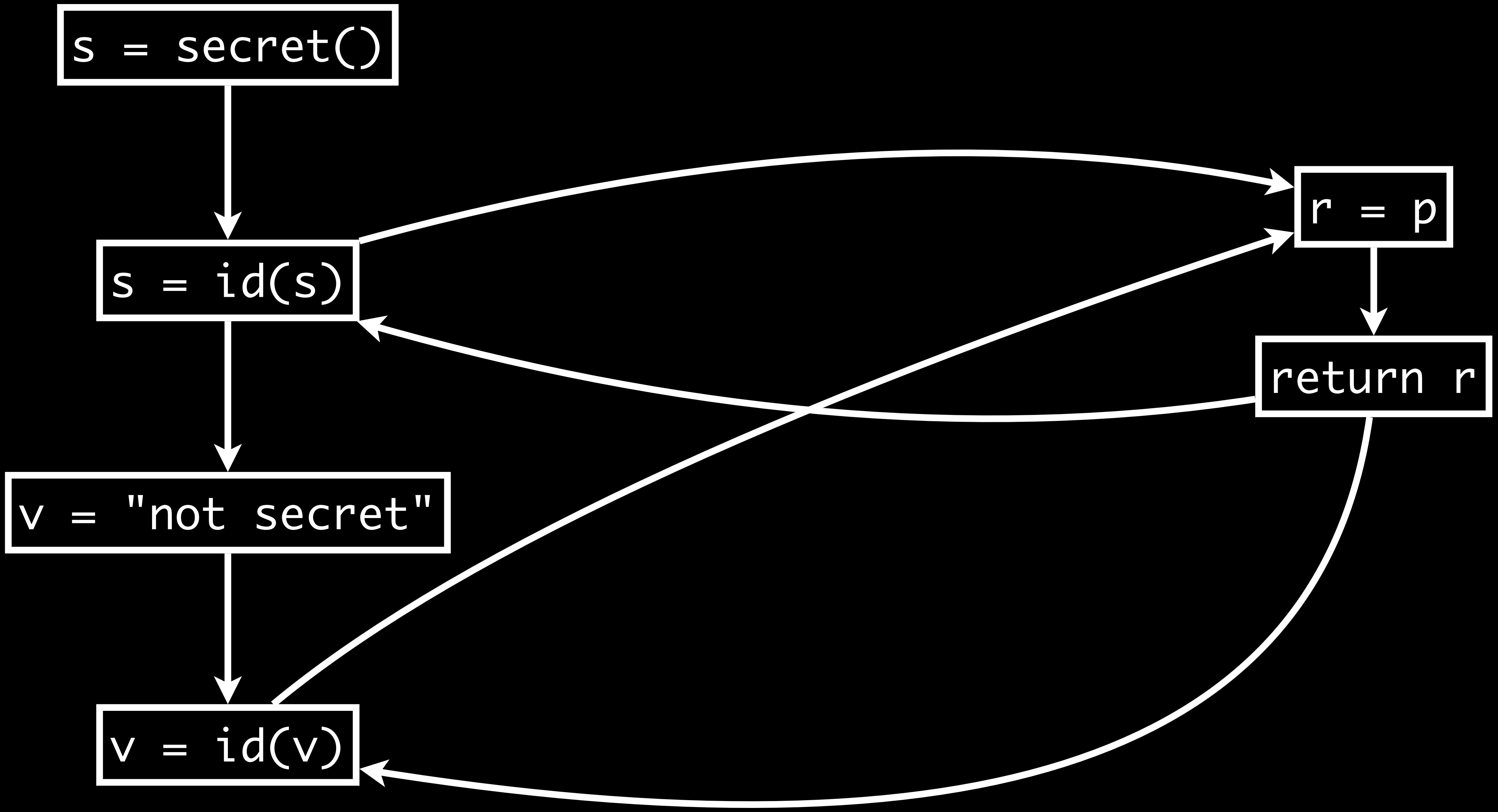
Call Strings

Call Strings

```
main(){
  s = secret();
  s = id(s);
  v = "not secret";
  v = id(v);
}
```

```
id(p){
  r = p;
  return r;
}
```

Call Strings



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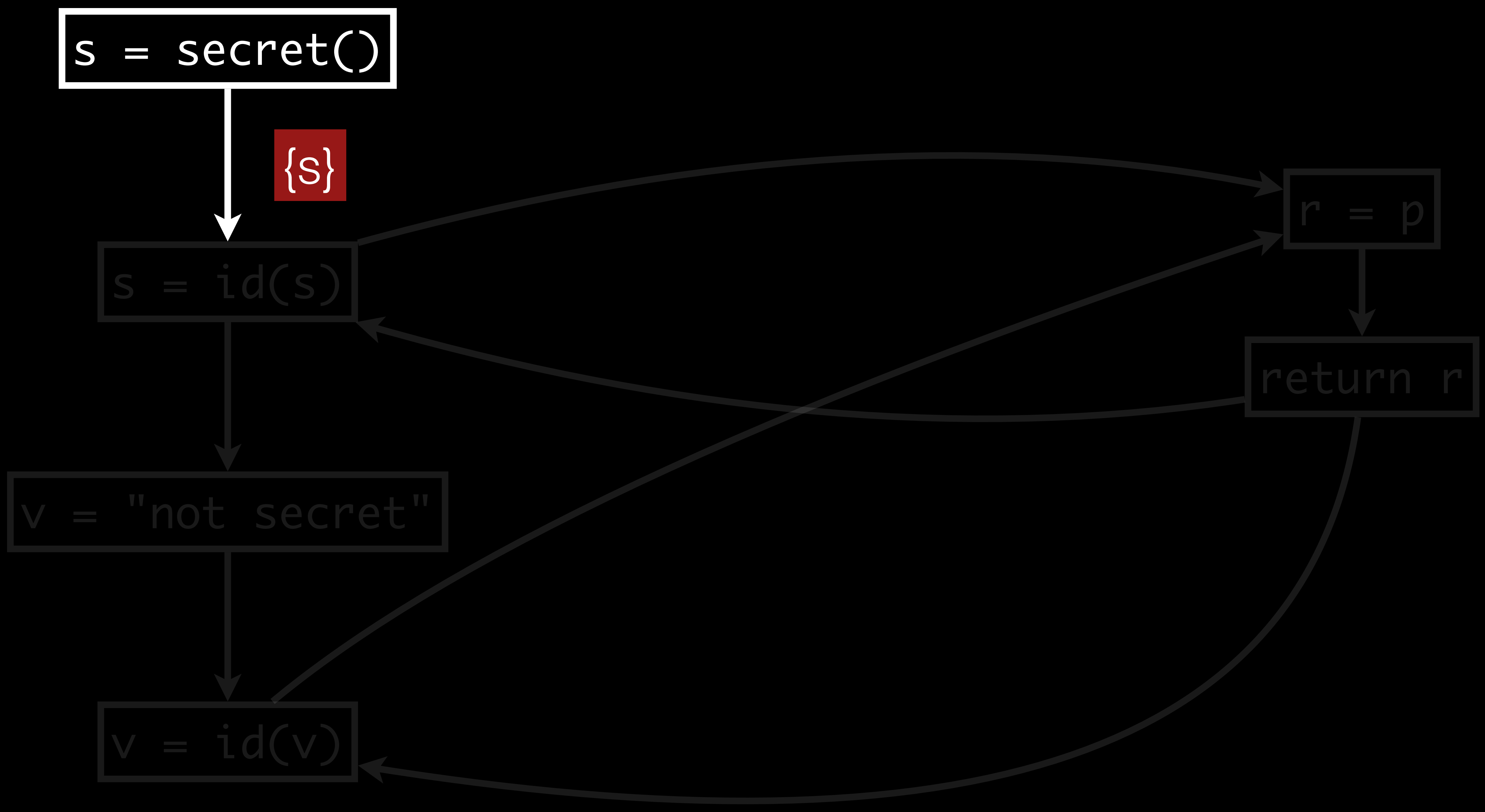

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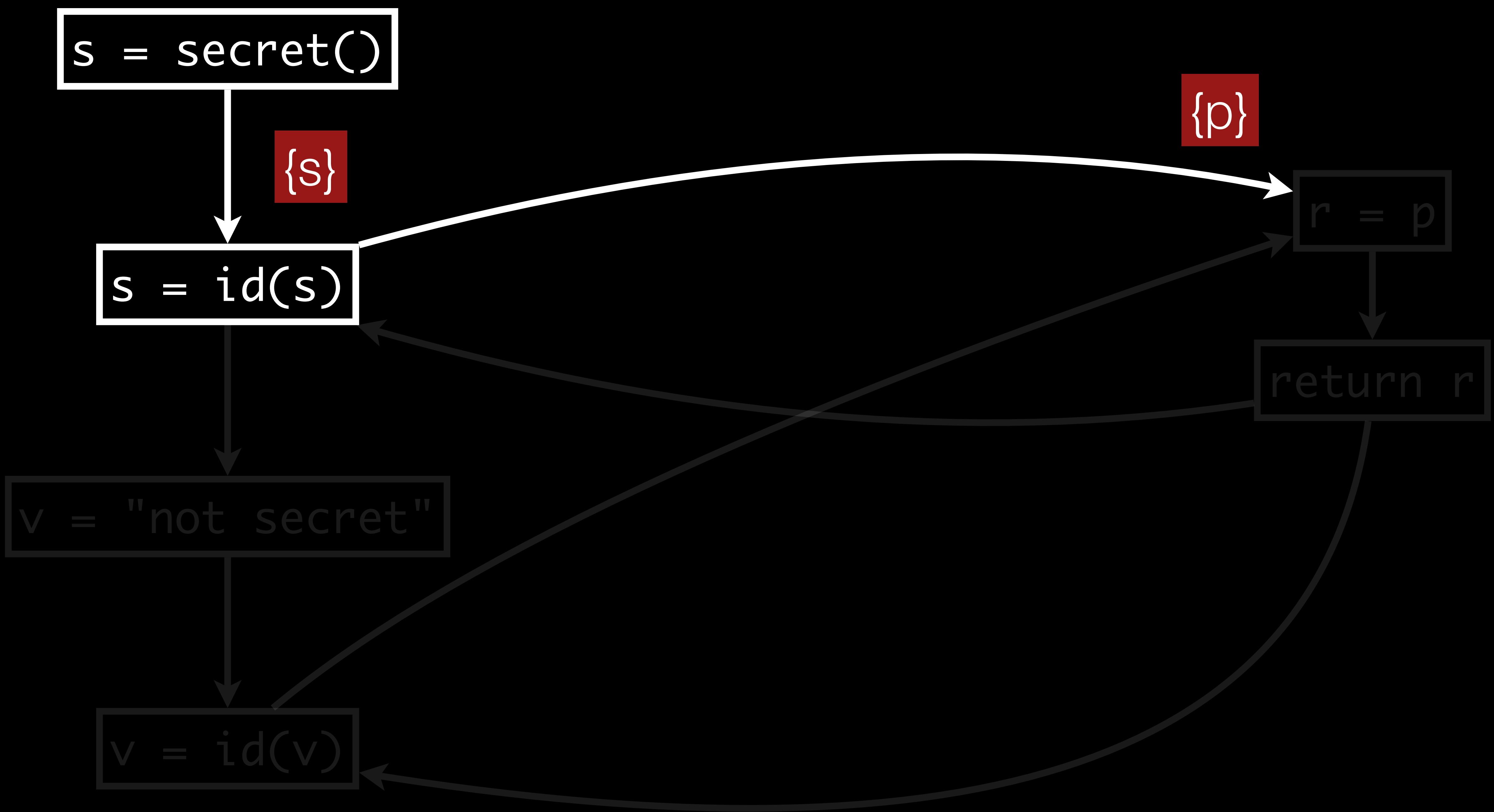

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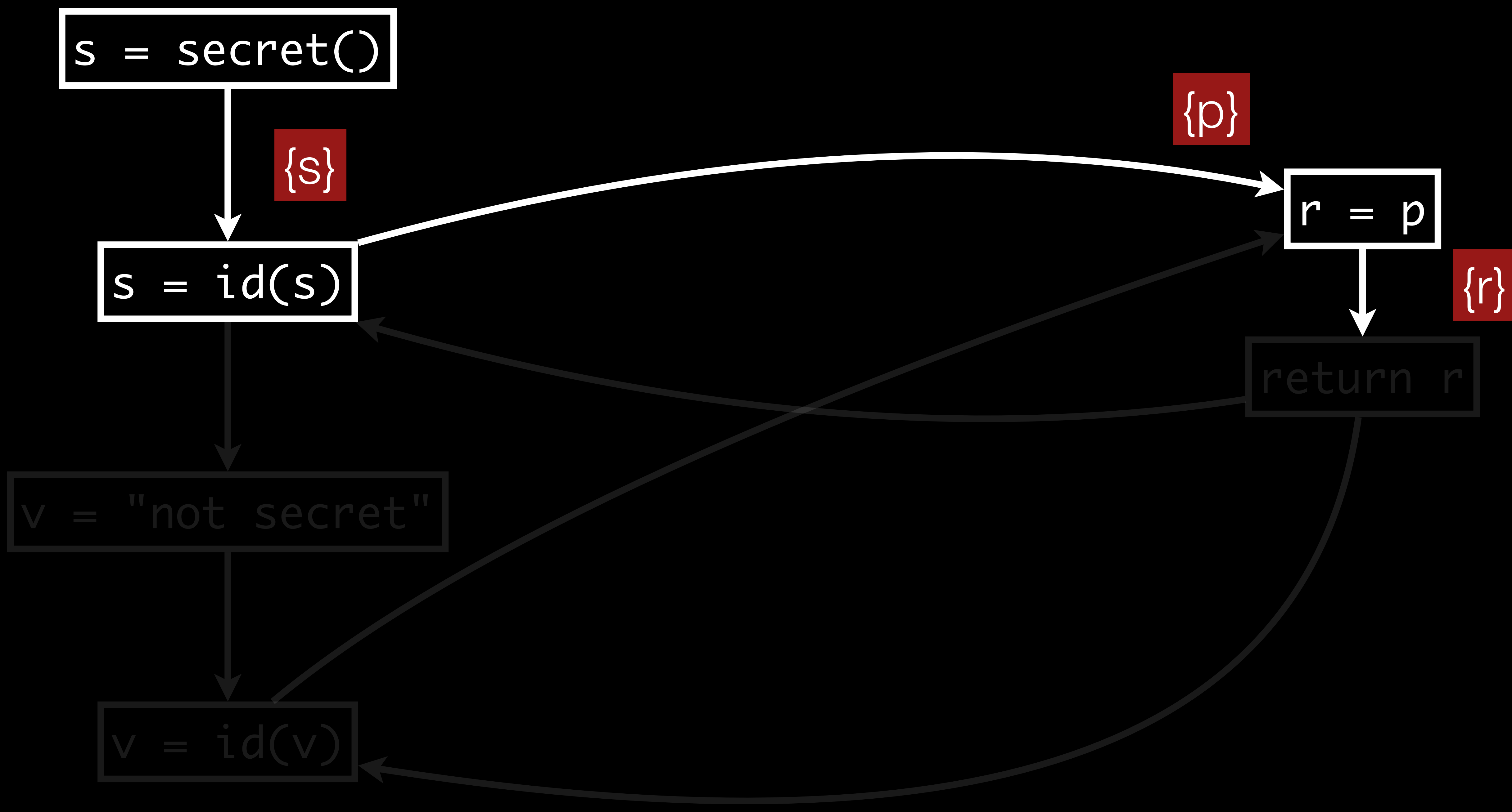

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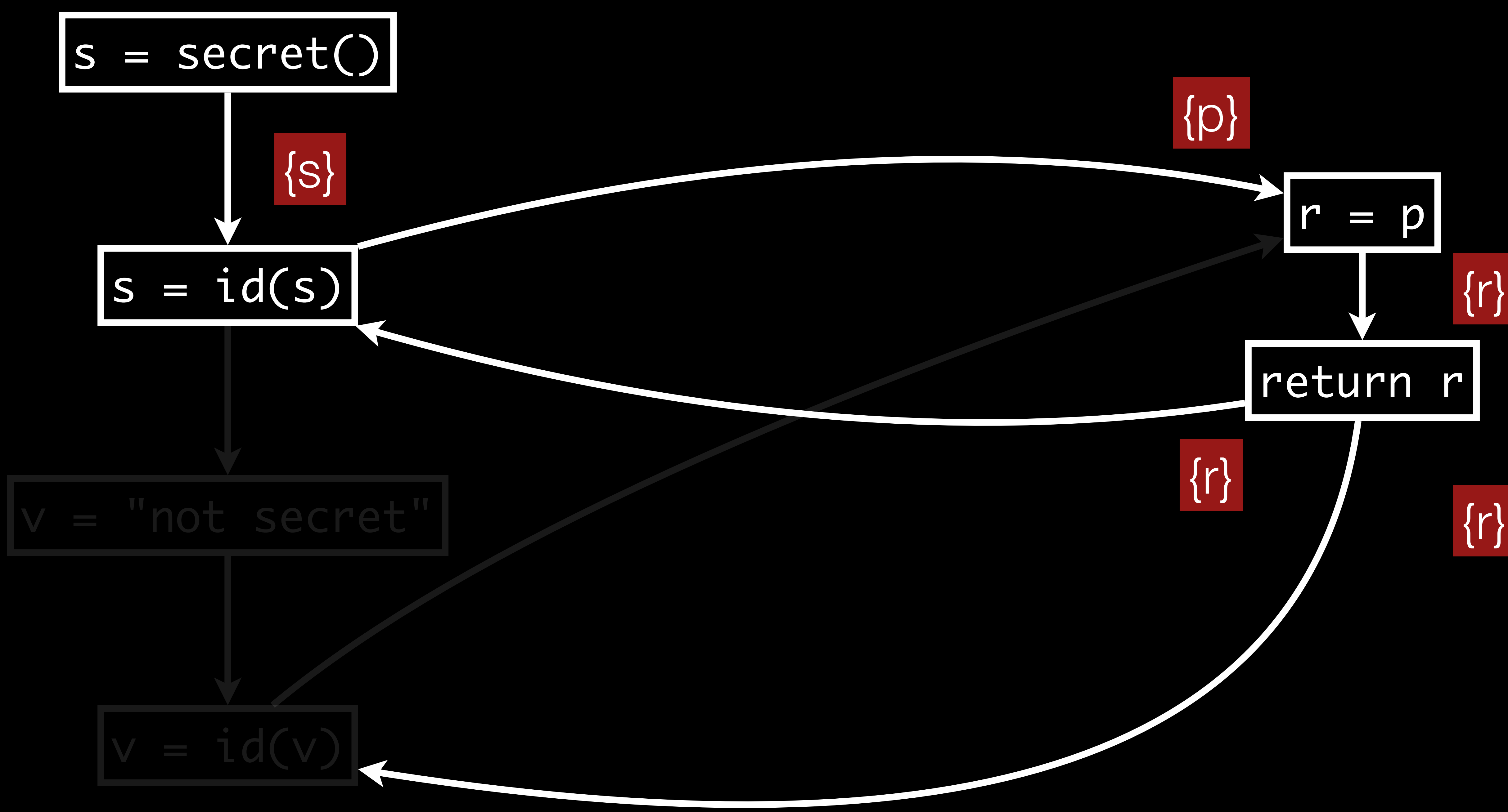

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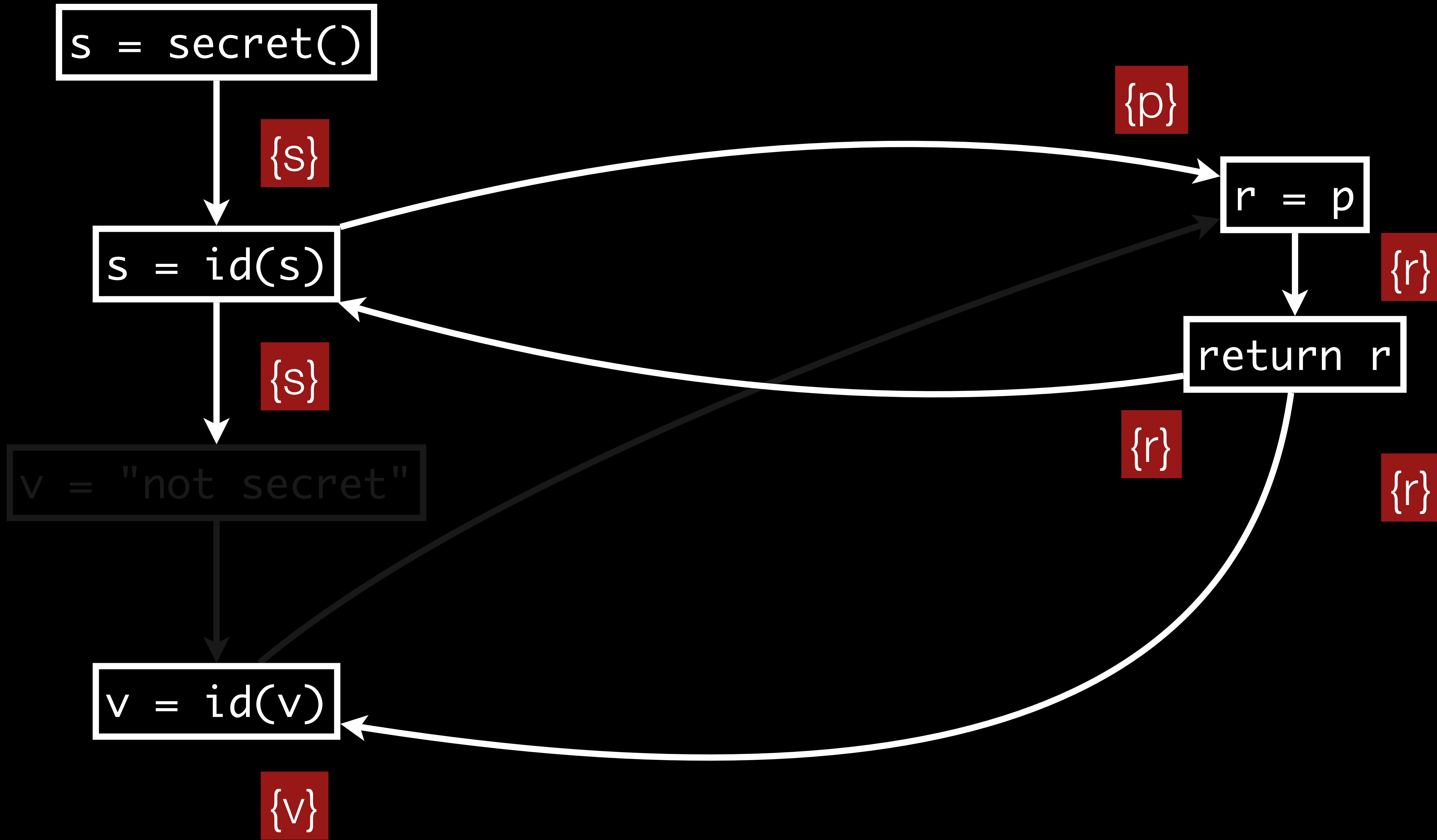

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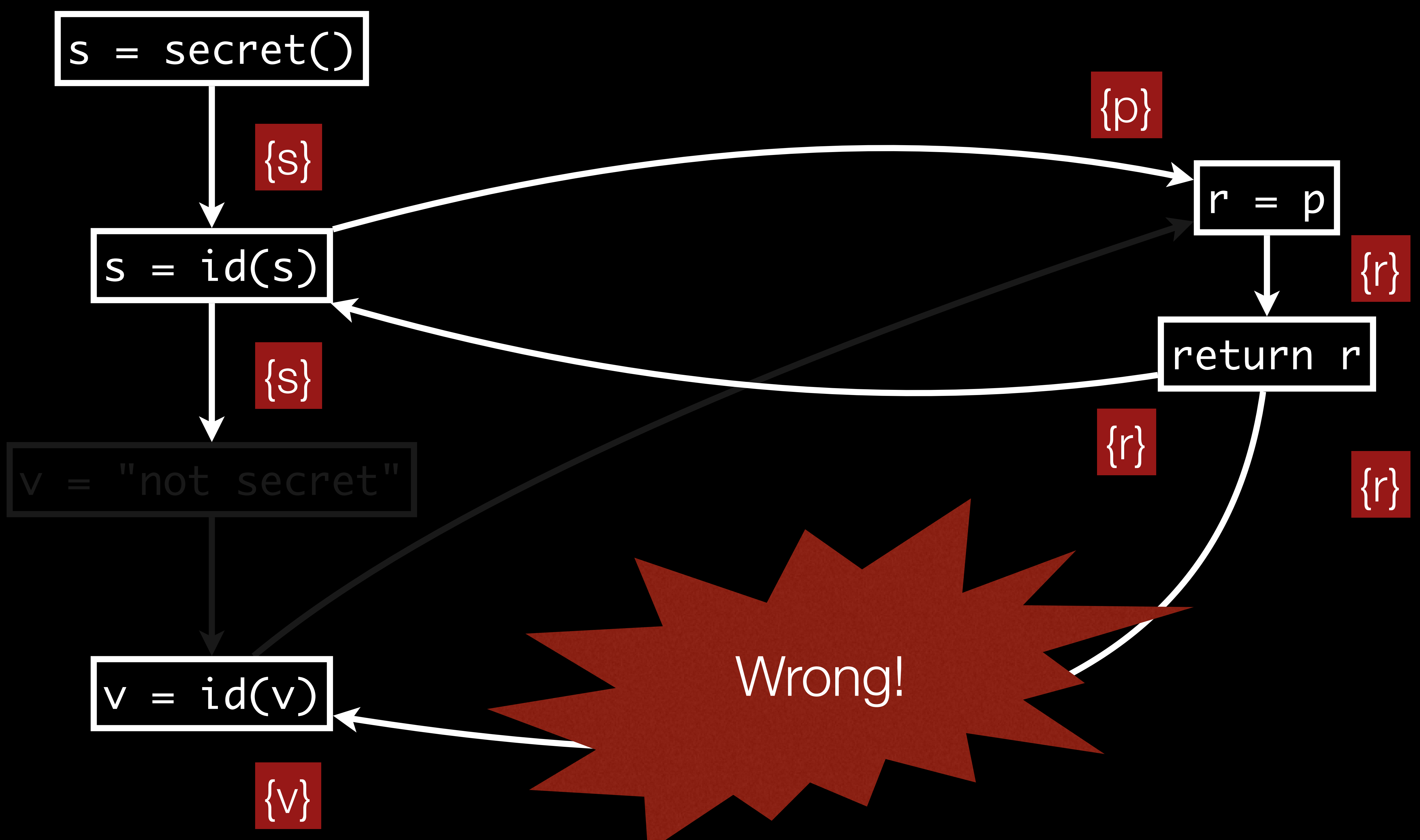

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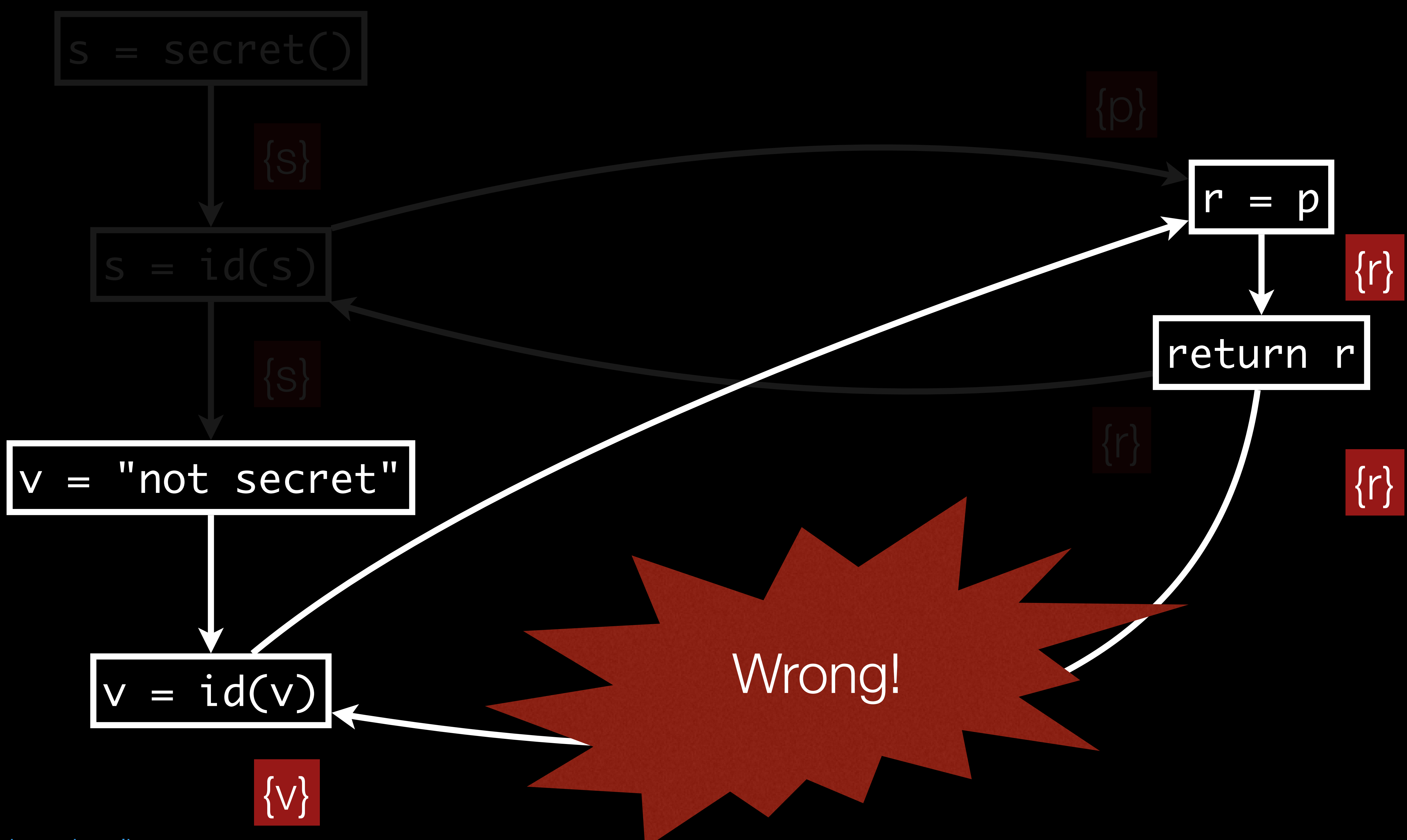

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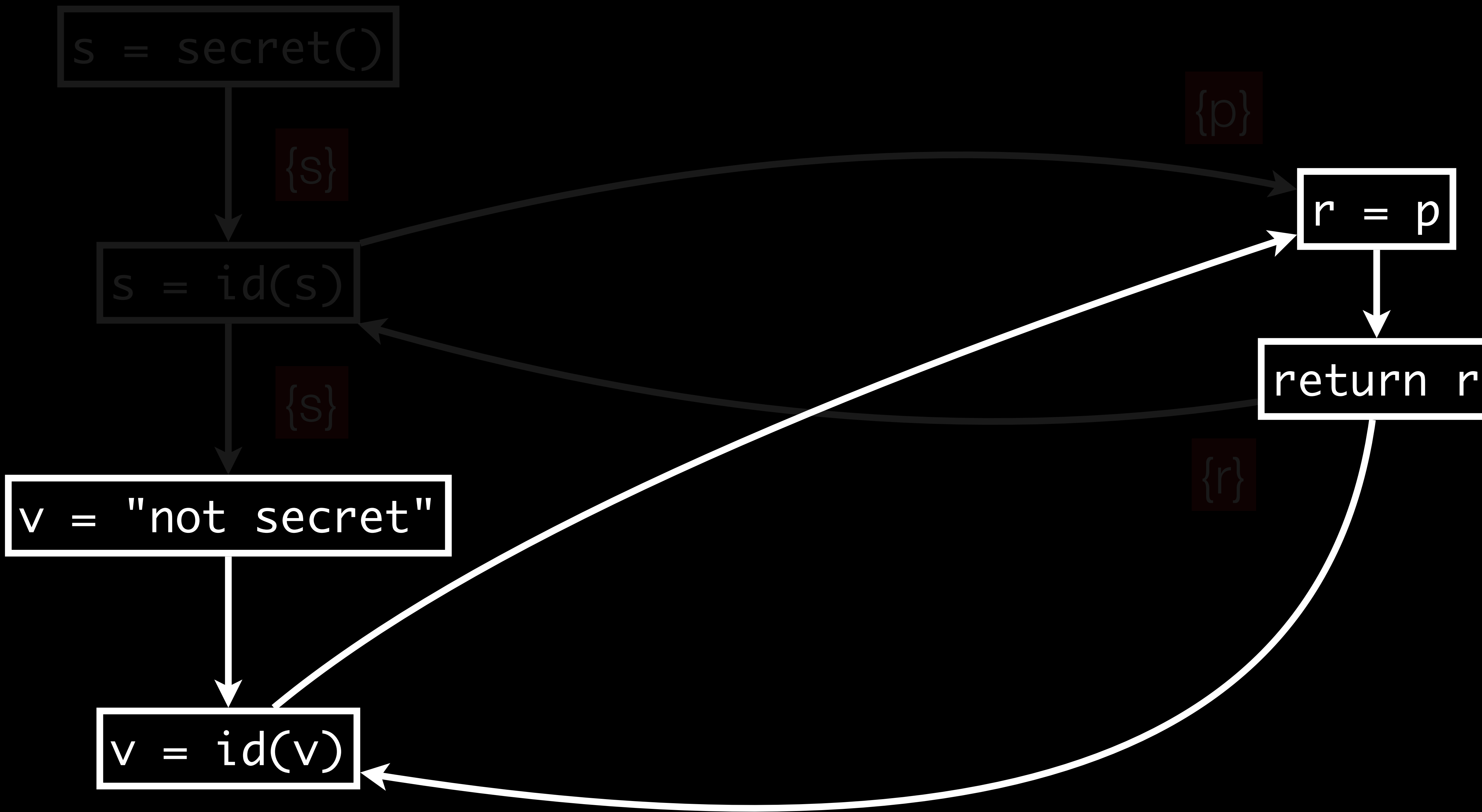

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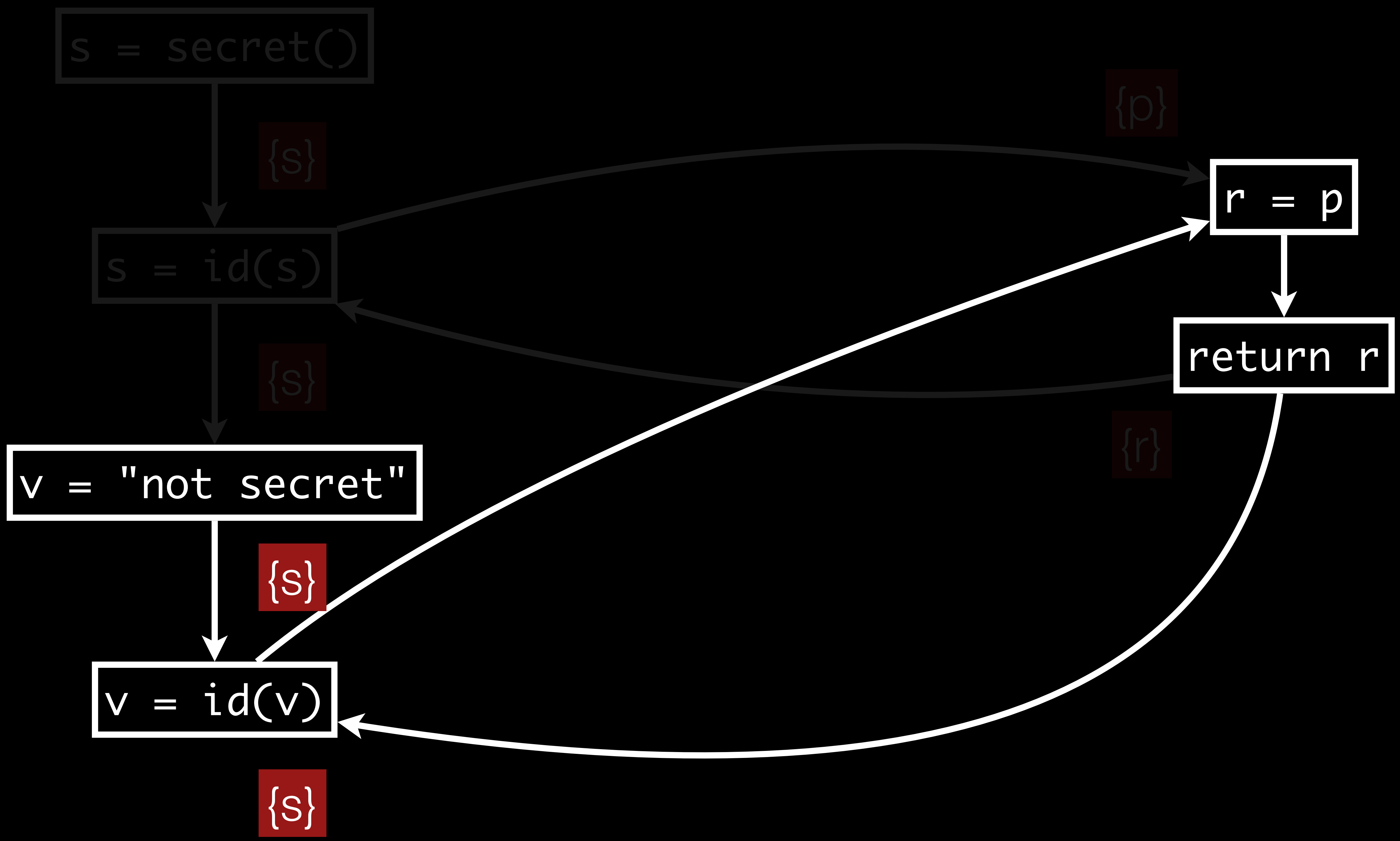

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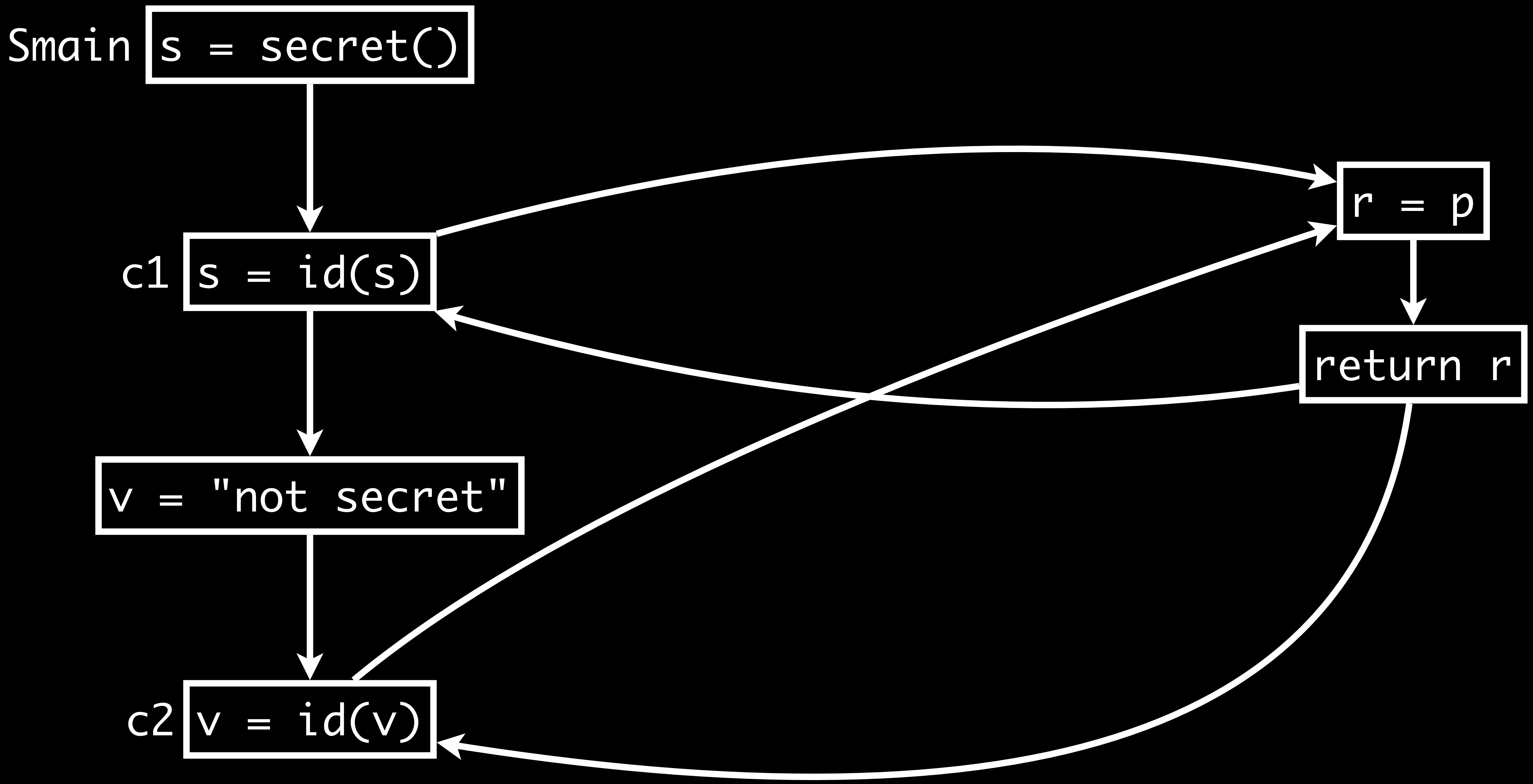

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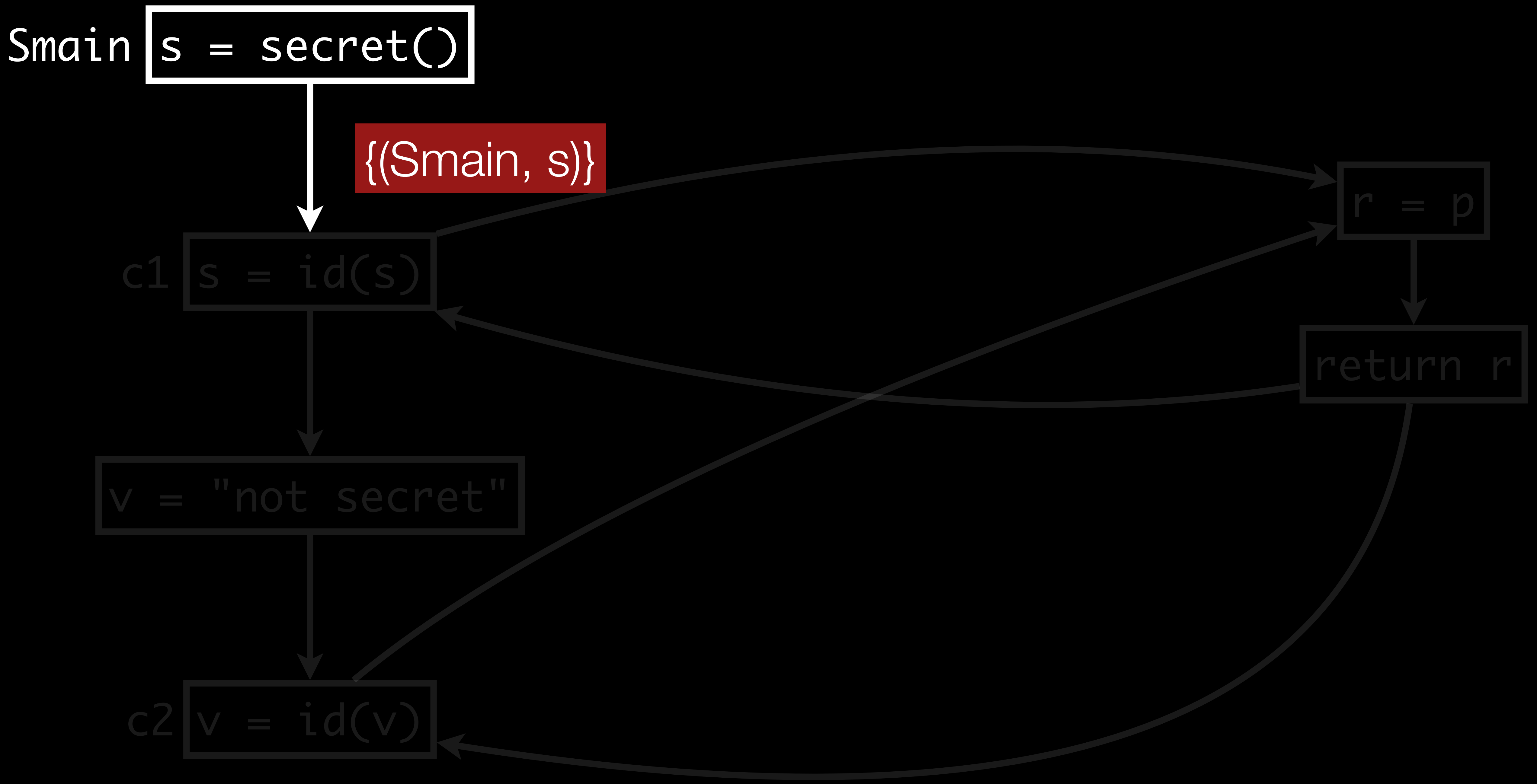

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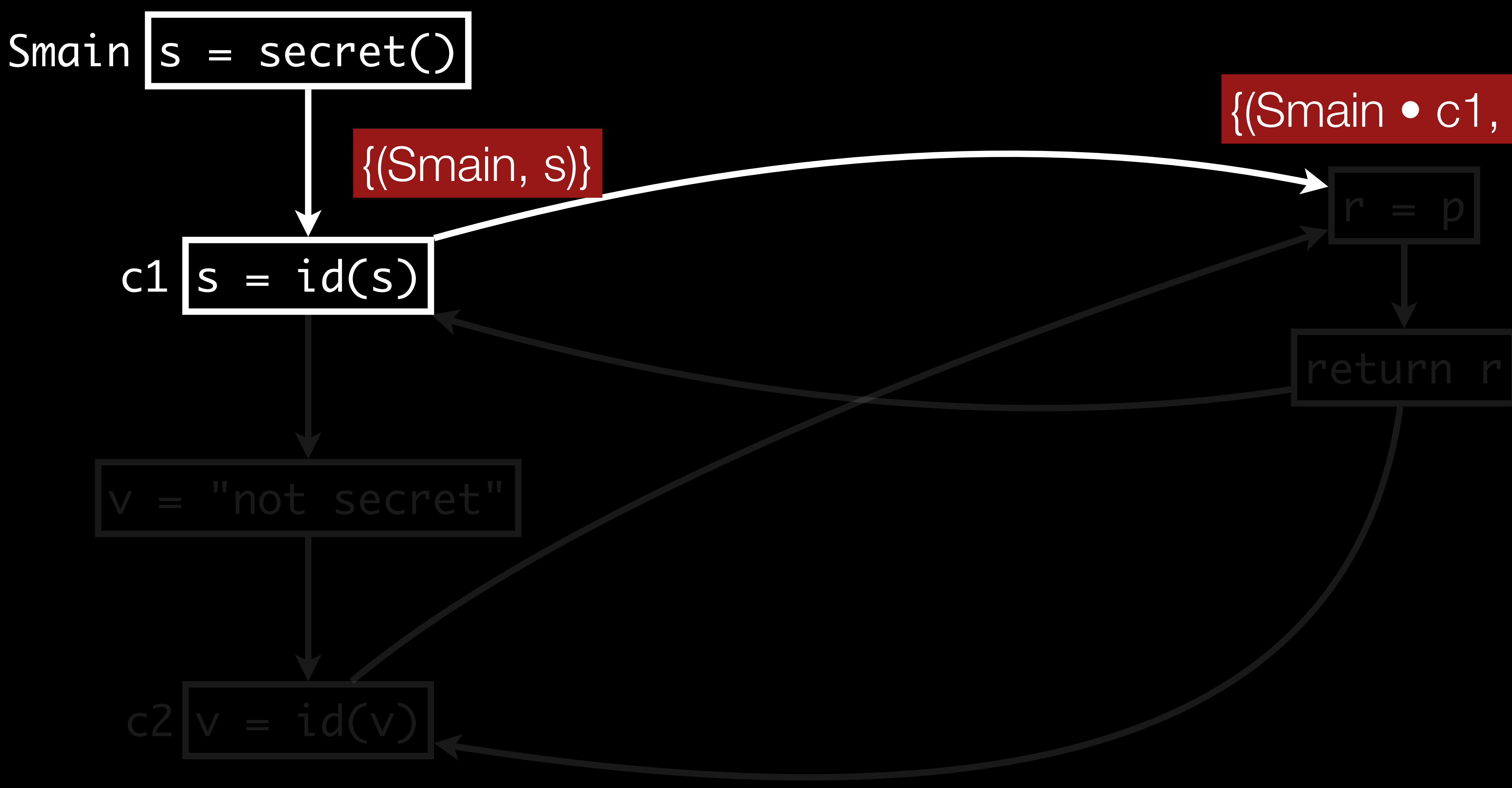

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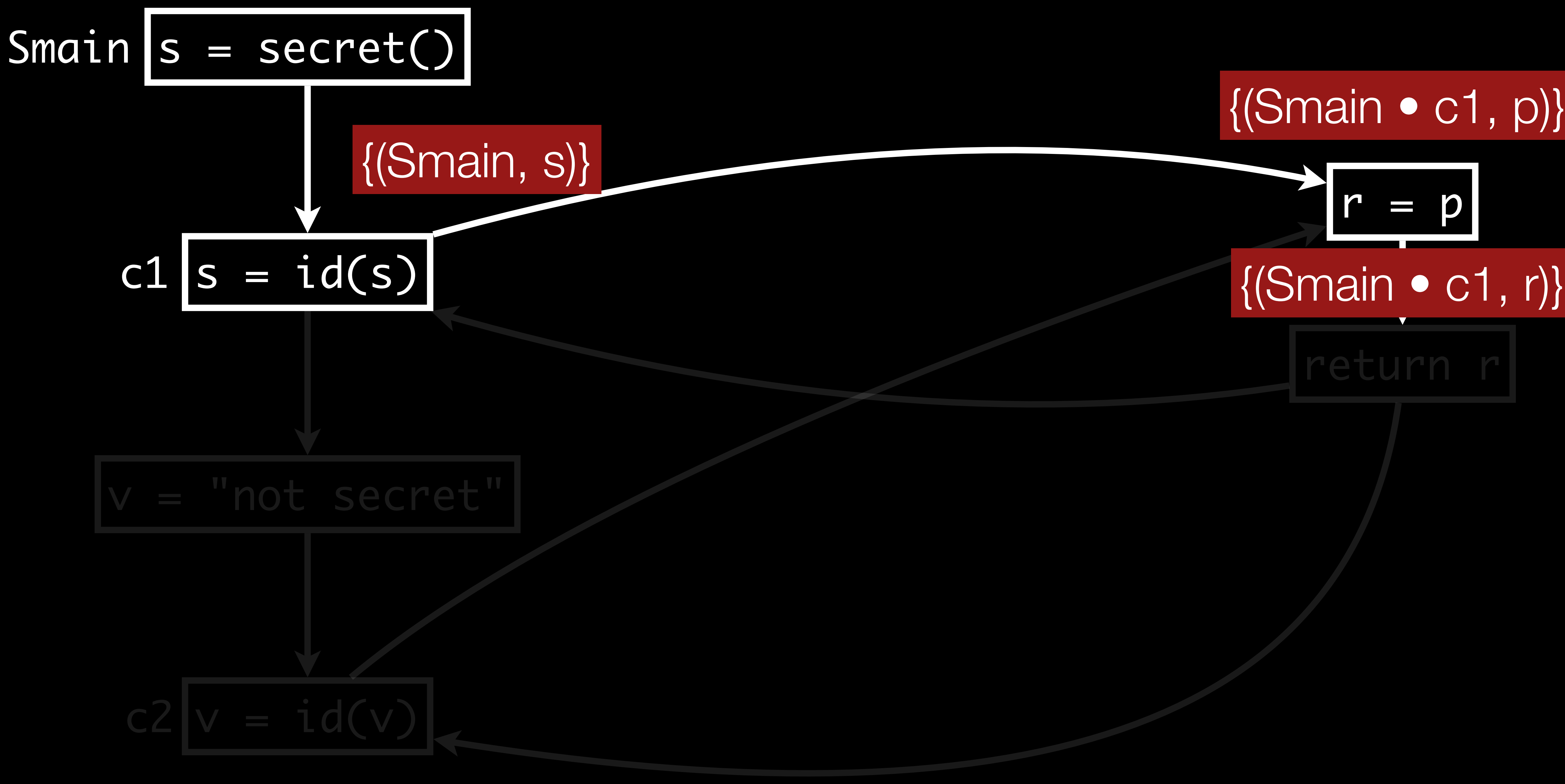

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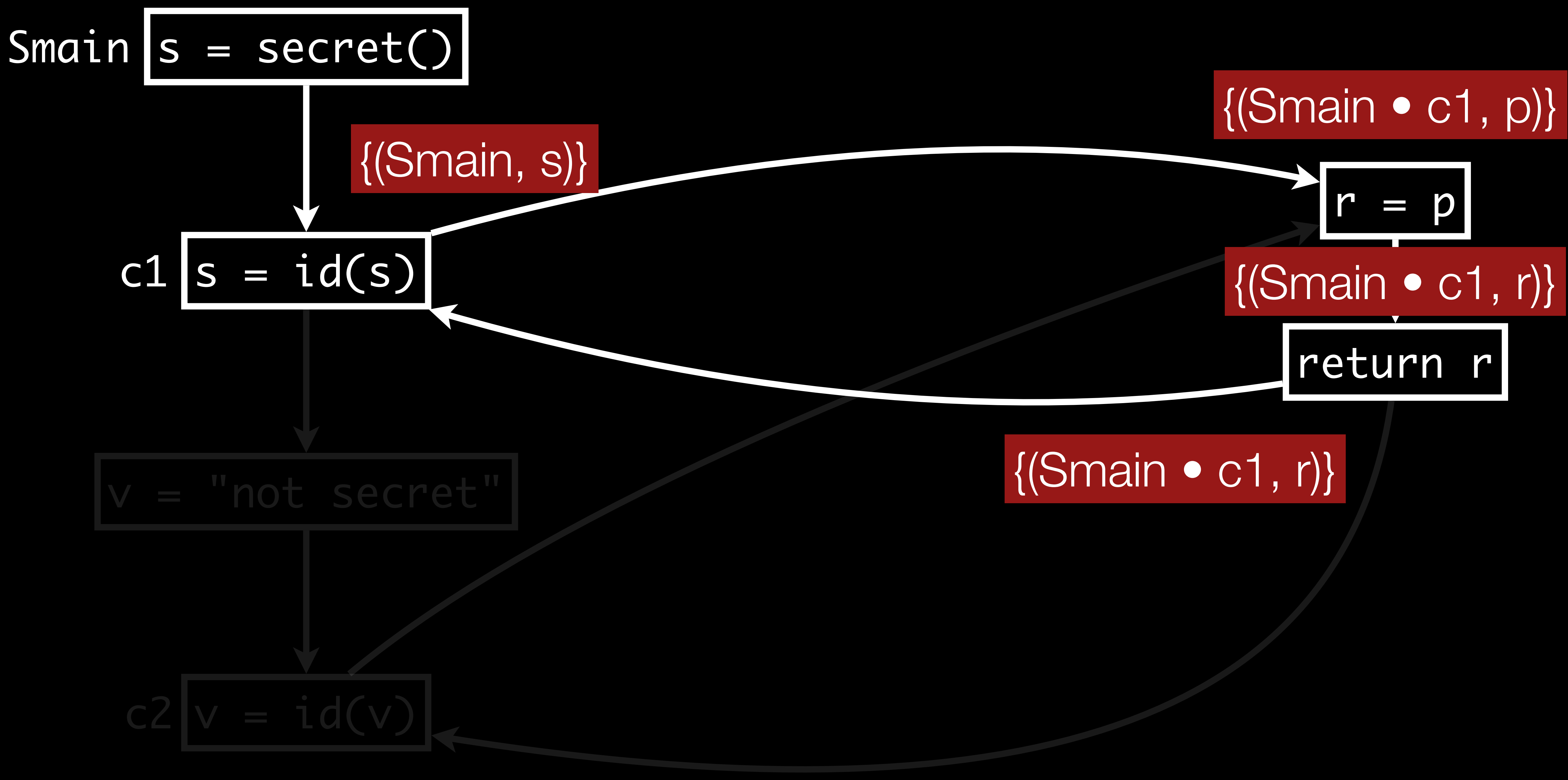

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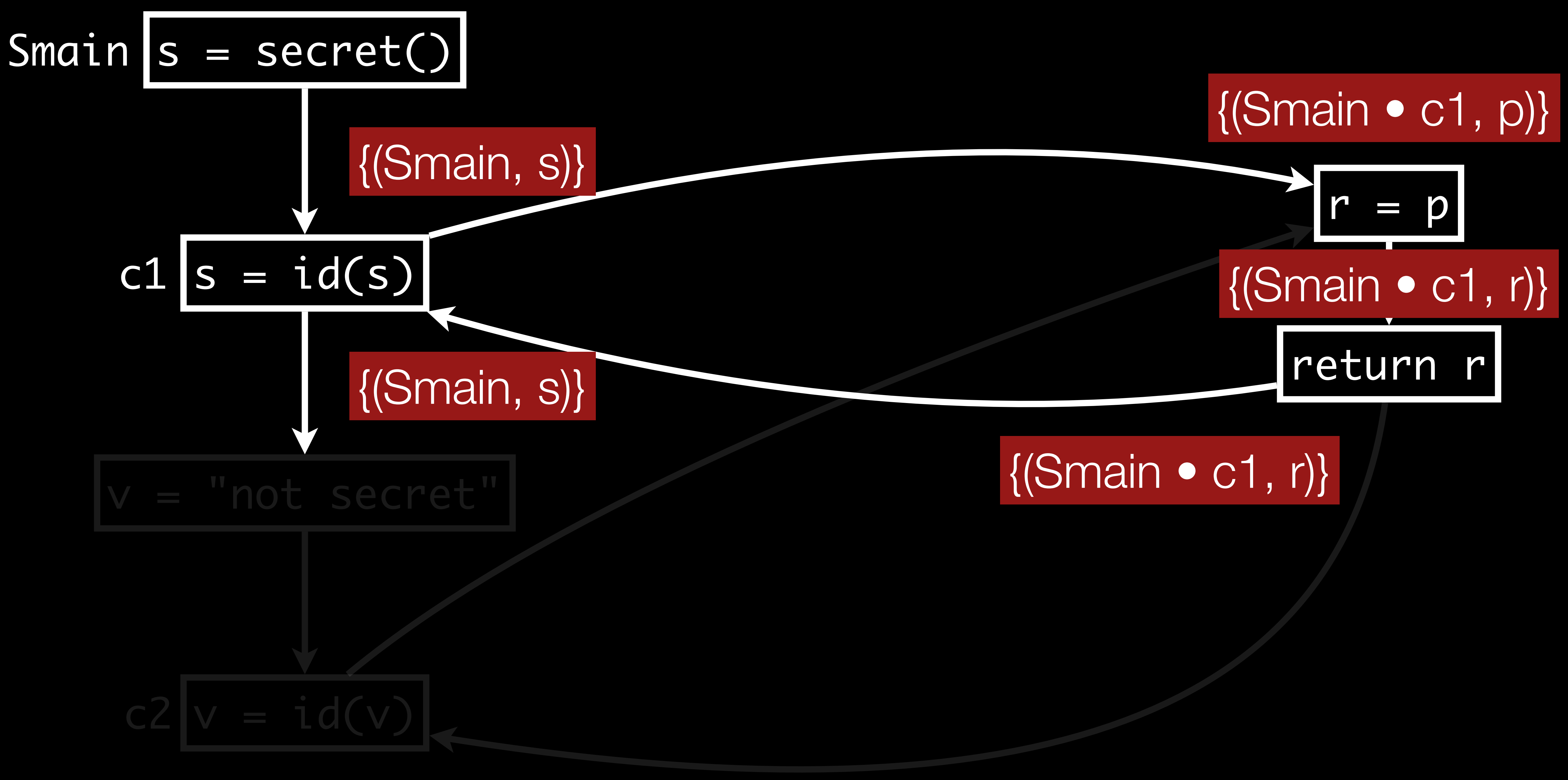

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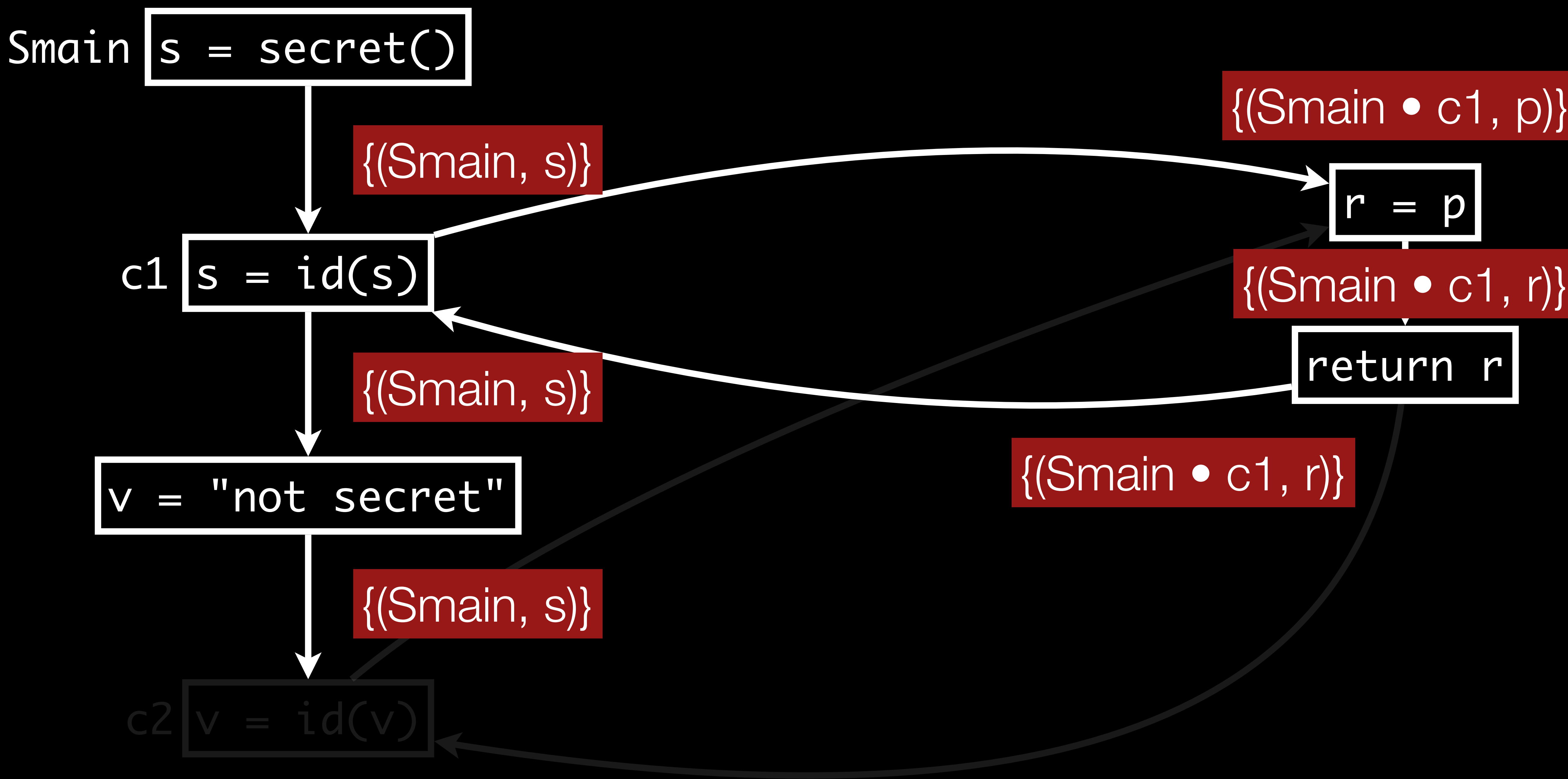

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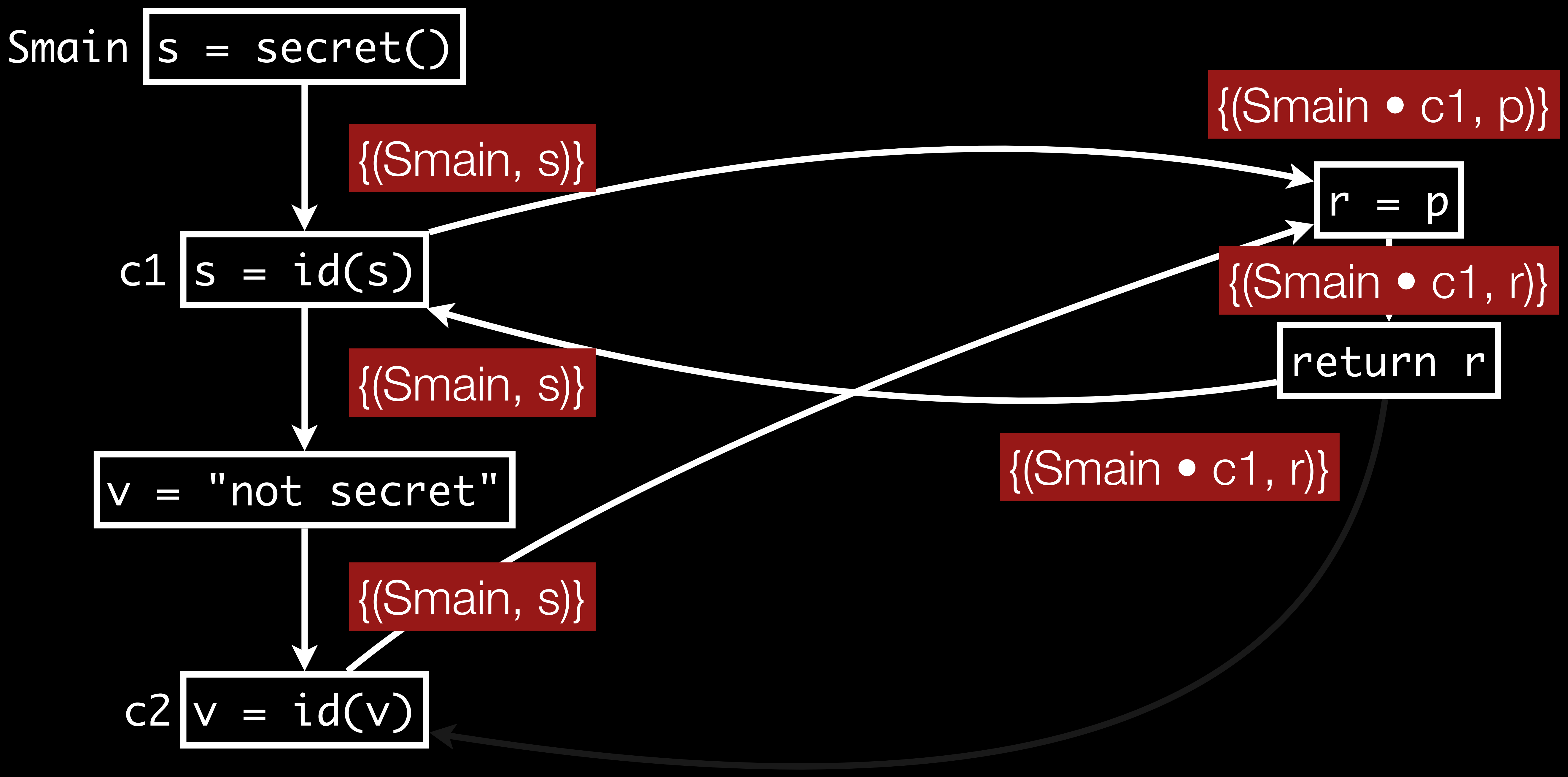

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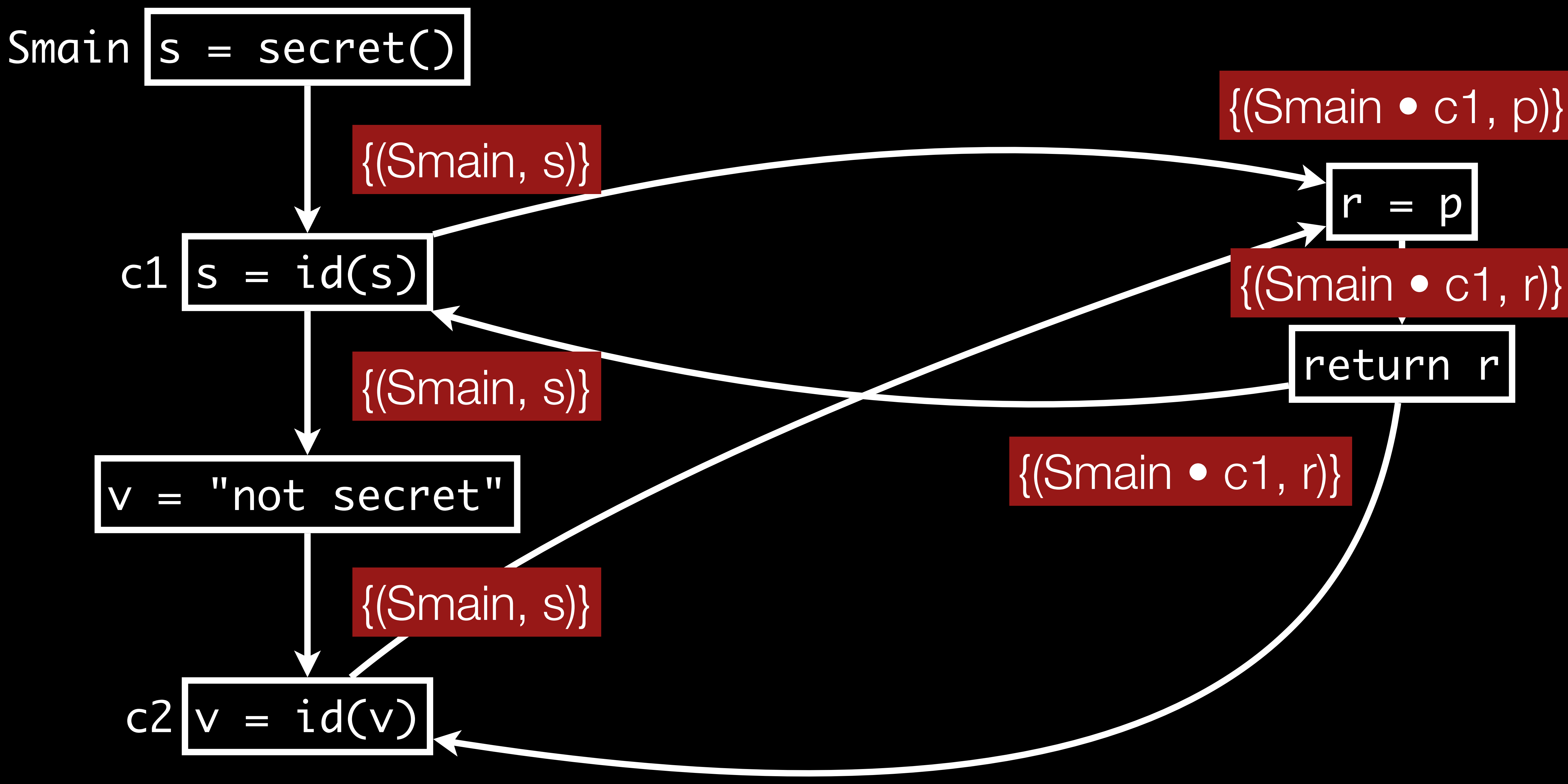

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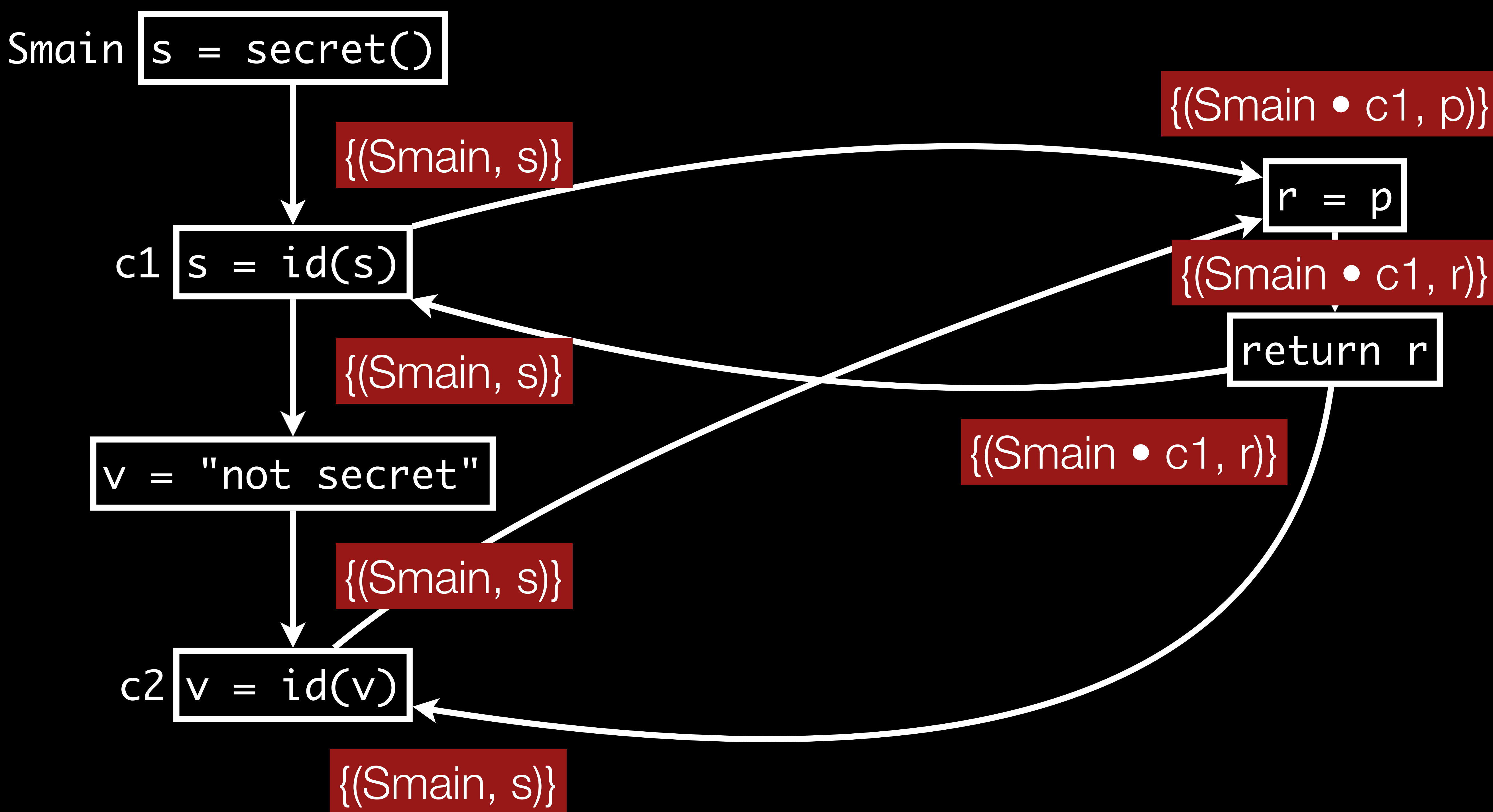

Call Strings
General Algorithm

- Call edges push call site to the stack of calling contexts of each propagated value
- Return edges return only to method on top of the stack of calling contexts
- Handle merge points

Call Strings
Merging Facts

$$X \uplus Y = \{ < \sigma, x \sqcup y > \mid < \sigma, x > \in X, < \sigma, y > \in Y \} \cup$$

$$\{ < \sigma, x > \mid < \sigma, x > \in X, \forall z \in L, < \sigma, z > \notin Y \} \cup$$

$$\{ < \sigma, y > \mid < \sigma, y > \in Y, \forall z \in L, < \sigma, z > \notin X \}$$

Not quite…

Problem:
context length!

Small k =>
imprecise

Solution:
k-limiting

large k =>
poor performance

… but how does it work anyways?

Call Strings
k-limiting

$$
\begin{array}{c}
k() \\
\downarrow \\
C_a \\
\downarrow \\
a()
\end{array}
$$

$(C_0 \bullet C_1 \bullet \ldots \bullet C_k)$

maintain suffix of length k

$(C_1 \bullet \ldots \bullet C_k \bullet C_a)$

Call Strings
k-limiting

- K = length of longest non-recursive call sequence
- $|L|$ = lattice height
- # contexts $= K * (|L| + 1)^2$
- Khedker and Karkare [CC '08] improved this bound to $K * (|L| + 1)$

Call Strings
Recap

- Cloning vs inlining
- Context as string
- Merging call strings
- Context length
- K-limiting

Functional Approach

… but why bother?

Functional Approach

```
  h.f = myPassword();
  i.f = myPhoneNo();
  j.f = myCreditCardNo();

c1 foo(h,x);
c2 foo(i,y);
c3 foo(j,z);

  print(x.g);
  print(y.g);
  print(z.g);
```

```
foo(a,b) {
  c = a.f;
  b.g = c;
}
```

Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();

c1 foo(h,x);                    foo(a,b) {     (a.f, c1)
c2 foo(i,y);                       c = a.f;
c3 foo(j,z);                       b.g = c;    (b.g, c1)
                                }

   print(x.g);
   print(y.g);
   print(z.g);
```

Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();

c1 foo(h,x);                 foo(a,b) {      (a.f, c2)
c2 foo(i,y);                    c = a.f;
c3 foo(j,z);                    b.g = c;     (b.g, c2)
                             }

   print(x.g);
   print(y.g);
   print(z.g);
```

Functional Approach

```
   h.f = myPassword();
   i.f = myPhoneNo();
   j.f = myCreditCardNo();

c1 foo(h,x);
c2 foo(i,y);
c3 foo(j,z);

   print(x.g);
   print(y.g);
   print(z.g);
```

```
foo(a,b) {          (a.f, c3)
  c = a.f;
  b.g = c;          (b.g, c3)
}
```

Functional Approach

```
h.f = myPassword();
i.f = myPhoneNo();
j.
c1
print(x.g);
print(y.g);
print(z.g);
```

Same method analyzed 3 times!!

```
foo(a,b) {
  c = a.f;
  b.g = c;
}
```

(a.f, c1)
(a.f, c2)
(a.f, c3)

(b.g, c3)
(b.g, c2)
(b.g, c1)

Functional Approach
Example: Constant Propagation

```
foo(a,b) {
  a++;
  return a+b;
}
```

Next

- IFDS